A unified phase diagram of domain walls in 1D systems, ranging from strips to cylindrical wires

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The research leading to these results has received funding from the European Union's 7th Framework Programme under grant agreement n°309589 (M3d)
**Motivation (general): magnetism towards 3D**

### Concepts for devices

- Domain walls in continuous wires
  - Scientific American, June, 76 (2009)
  - + patents (IBM)

- Solitons in stacks of elements

### 3D magnetic objects and textures

- Magnetic meron
  - S. Wintz et al., PRL 110, 177201 (2013)

- 3D objects
  - C. Donnelly et al., PRL 114, 115501 (2015)

Interest in examining and classifying 3D magnetic textures
Motivation (focused): domain walls in strips and wires

**Flat strips**

- Transverse wall (TW)
- Vortex wall (VW)

Transition for: \(tW \approx 61 \Delta^2_d\)


**Cylindrical (or square) wires**

- Transverse wall
- Bloch-point wall (BPW)

Transition for: \(d \approx 7 \Delta_d\)

S. Da-Col et al., PRB 89, 180405 (2014)
H. Forster et al., JAP 91, 6914 (2002)

**Open questions**

- What about VWs in wires?
- Do BPWs exist in rectangular wires?
- Difficulty to visualize a 3D vector field
- How to classify simply domain walls?

**Example of confusing vocabulary for wires**

- Bloch-point wall = Vortex wall, pseudo-vortex wall...
- Transverse wall = pseudo TW, asymmetric TW, vortex/antivortex wall, corkscrew...
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The known phase diagram for transverse and vortex walls in strips

Y. Nakatani et al., JMMM290, 750 (2005)

First order transition

- Abrupt transformation between two separated energy wells
- Metastability of the two states

Second order transition

- Continuous transition with an order parameter
- No metastability: only one state exists at a time
- Breaking of symmetry

See phase transitions in micromagnetism:

First-order transitions between transverse and vortex walls

- It is possible to transform continuously a transverse wall into a vortex wall.
- They share the same topology.
- They should be degenerate on the diagonal.
- The equilibrium line is symmetric with the diagonal.
Curling in transverse walls

Different views of transverse walls

Square side : 30nm

- At large diameter walls have both vortex and transverse features
- May be shortened to 'vortex' or 'transverse' if dominating feature
- Do not use 'vortex' for 'Bloch-point' to avoid confusion

Vorticity = Curling = Rotational

Square side : 44nm

$D \lesssim 7 \Delta_d$

$D \gtrsim 7 \Delta_d$
Quantify curling in the Transverse/Vortex wall

Circulation of magnetization $\rightarrow$ Quantify curling

\[
\text{div} \, \mathbf{M} \approx -\frac{d M_z}{dz}
\]

- Vortex feature = transverse curling
- Second-order transition for $D \approx 7 \Delta_d$
- Longitudinal curling arises to decrease dipolar energy
Phase second-order transition in strips: asymmetric transverse walls (Guess)

- Analogy between the asymmetric transverse wall and the Néel / Bloch wall transition
- What about asymmetry versus vorticity?

1: TW
2, 6: Asymmetric TW
3: Néel walls
4: Bloch walls
5: TVW
Second-order transition: simulation tells about asymmetry versus curling

Both instabilities arise in order to decrease magnetostatic energy (split charges apart)

- Curling takes over asymmetric walls for a thickness larger than \(7 \Delta_d\)
- Curling can be viewed as built with opposite asymmetries on either side
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The known transition for domain walls in wires (disks or squares)

Transverse wall \( D \lesssim 7 \Delta_d \)


Bloch-point wall \( D \gtrsim 7 \Delta_d \)

- Sometimes improperly named vortex walls

**What is a Bloch-point?**

A magnetic texture with local cancellation of the magnetization vector

- R. Feldkeller, Z. Angew. Physik 19, 530 (1965)
First-order transitions between transverse-vortex walls and Bloch-point walls

1: TW < VW < BPW
2: TW < BPW < VW
3: VW < TW < BPW
4: VW < BPW < TW
5: BPW < TW < VW
6: BPW < VW < TW

- Two equilibrium lines exist: BPW/x-TVW, and BPW/y-TVW
- The equilibrium lines are symmetric with each other around the diagonal
- If $D_{BP} < D_{TW}$ there must exist three triple points

1: TW < VW < BPW
2: TW < BPW < VW
3: VW < TW < BPW
4: VW < BPW < TW
5: BPW < TW < VW
6: BPW < VW < TW
**Quantify domain wall length**

### Experiments
- **Wire Diameter**: 95nm
- **Wire Diameter**: 70nm
- **Shadow**

### Analytics
- **Physics**: balance exchange and dipolar energies
- **Energy**: $\mathcal{E} \sim AR^2/\Delta d$
- **Wall length**: $L \sim R^2/\Delta d$

### Simulations
- **Graph**: Confirmation of scaling law for wall length $L \sim R^2/\Delta d$

- **Notes**:
  - Sharp increase of length with diameter
  - Longitudinal curling is shared by the TVW and BPW
Formal identification of domain walls

Bloch-Point Wall (BPW)

- Wire diameter: 95 nm
- Orthoradial curling
- Symmetry with respect to plane perpendicular to axis

Transverse Wall (TW)

- Wire diameter: 70 nm
- Loss of symmetry with respect to plane perpendicular to axis

N. Bizière et al., Nanolett. 13, 2053 (2013)

Phase diagram confirmed by simulation
Domain-walls in one-dimensional systems

- Transverse (TW)
- Vortex
- Bloch
- Néel

Transverse and vortex walls share the same topology

Bloch-point domain walls are of a different class

Topological protection

Strips and transverse walls

- Theory and experiments
- Domain-wall transformation
- Walker limit, low speed (~100m/s)

BPW in wires (similar physics for tubes)

- Theory predictions; no experiments
- No domain-wall transformation
- High speed expected (>1 km/s)

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Domain-wall motion in wires (here: under field)

**LLG equation**

\[
\frac{d\mathbf{m}}{dt} = \gamma_0 \mathbf{m} \times \mathbf{H} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt}
\]

\(\gamma_0 < 0\)

**Once-only 'Walker' field for switching the orthoradial circulation**

- Dynamically locked
- Once-only 'Walker' process for the circulation
- Right-hand rule: DW direction of motion vs circulation
- Same physics predicted (later) for nanotubes

Propogation and selection of circulation: preliminary data

**Structure**

Focus on wire

Focus on shadow

**Motion and circulation**

Initialize  
Field pulse  
Final state

- Bloch-Point walls with same circulation

_confirmation_: selection of circulation with once-only Walker switch (preliminary)
Conclusions and VIPs

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C. Thirion  
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- Only two topologies: transverse/vortex and Bloch-point walls
- Full phase diagram width / thickness derived
- Curling and asymmetries described as second-order transitions. They allow to decrease magnetostatic energy for $D \geq 7 \Delta_d$
- No asymmetric TWs in wires (transverse is more efficient to decrease energy)
- Bloch walls exist and is ground state for a large range of geometries

Experimental contrast

Two examples

Beam along wire
⇒ Locate domain walls

Beam across wire
⇒ Inspect domain wall

Several non-trivial patterns

Need for modelling